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Towards a revised coefficient for estimating N_2O emissions from legumes

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Abstract

The Intergovernmental Panel on Climate Change (IPCC) standard methodology to conduct national inventories of soil N_2O emissions is based on default (or Tier I) emission factors for various sources. The objective of our study was to summarize recent N_2O flux data from agricultural legume crops to assess the emission factor associated with rhizobial nitrogen fixation. Average N_2O emissions from legumes are 1.0 kg N ha^{-1} for annual crops, 1.8 kg N ha^{-1} for pure forage crops and 0.4 kg N ha^{-1} for grass legume mixes. These values are only slightly greater than background emissions from agricultural crops and are much lower that those predicted using 1996 IPCC methodology. These field flux measurements and other process-level studies offer little support for the use of an emission factor for biological N fixation (BNF) by legume crops equal to that for fertiliser N. We conclude that much of the increase in soil N_2O emissions in legume crops may be attributable to the N release from root exudates during the growing season and from decomposition of crop residues after harvest, rather than from BNF *per se*. Consequently, we propose that the biological fixation process itself be removed from the IPCC N_2O inventory methodology, and that N_2O emissions induced by the growth of legume crops be estimated solely as a function of crop residue decomposition using an estimate of above- and below-ground residue inputs, modified as necessary to reflect recent findings on N allocation.

Introduction

International initiatives such as the United Nations Framework Convention on Climate Change and the Kyoto Protocol require countries to calculate national inventories of greenhouse gas (GHG) emissions. In 1996, the Intergovernmental Panel on Climate Change (IPCC) proposed a standard methodology to conduct inventories of GHG emissions from various sectors of human activity (IPCC 1997). This procedure included default (or Tier I) emission factors for N_2O sources in agricultural soils such as application of nitrogen fertilizer or animal manure, decomposition of crop residues and biological nitrogen fixation (BNF). New studies published since 1996 may allow modifications of the IPCC methodology, notably of the BNF emission factor.

About 30–40 million tonnes of atmospheric N_2 are fixed every year by bacteria in symbiosis with legume crops (Jenkinson 2001; Smil 2002a, b; Galloway et al. 2003). According to the current IPCC methodology, this nitrogen (N) can produce N_2O in two ways: N_2O can be produced during biological N fixation itself, and N_2O can be produced when legume residues are returned to the

soil. The latter route is well-established – when residues rich in N (low C:N ratio) decompose in soil, they can release large amounts of mineral N which is then susceptible to N_2O loss during nitrification and denitrification (Aoyama and Nozawa 1993; Larsson et al. 1998; Baggs et al. 2000; Yang et al. 2002; Huang et al. 2004; Rochette et al. 2004). Accordingly, incorporating legume residues can result in higher N_2O–N losses than those from non-legume residues (e.g., Millar et al. 2004).

Clearly, legumes can produce substantial N_2O when their residues decompose. But emissions from the other pathway – during fixation itself – seem less certain. Some studies have shown that several *Rhizobium* species, in the free-living form, in legume root nodules or as isolated bacteroids, can denitrify nitrate and release N_2O (O'Hara et al. 1984; Bryan et al. 1985; O'Hara and Daniel 1985; van Berkum and Keyser 1985; Smith and Smith 1986; Bonish et al. 1991; Garcia-Plazaola et al. 1993a; Garcia-Plazaola et al. 1996; Rosen et al. 1996). This denitrification may have several benefits for *Rhizobia*. It eliminates nitrate that inhibits nitrogenase activity in nodules (Luciñski et al. 2002) and nitrite that prevents Rhizobial infection of legume roots (Munns 1977). Denitrification also removes toxic nitrite and may supply energy during nitrate respiration (O'Hara and Daniel 1985; Arrese-Igor et al. 1990; Garcia-Plazaola et al. 1993a). Some strains of *Rhizobium* can reduce NO_3^- completely to N_2 but the end product of the most active denitrifying *Rhizobia* seems to be N_2O (O'Hara and Daniel 1985).

While studies have shown that some *Rhizobia* can denitrify nitrate, the rate at which this process occurs seems to vary, depending on species. For example, Rosen et al. (1996) "found a great variety regarding the denitrification capacity within *R. meliloti* strains, most of them with low or no detectable activity." Furthermore, the significance of *Rhizobia* denitrification in the field is still debated (Breitenbeck and Bremner 1989; Luciñsky et al. 2002). O'Hara and Daniel (1985) suggested that rhizobial "denitrification can occur in normally-aerated soil" and that "On an area basis, the nitrogen losses are similar in magnitude to the nitrogen gained by symbiotic rhizobial nitrogen fixation, even when soil numbers of rhizobial are quite moderate". In contrast, Garcia-Plazaola et al. (1993b) concluded more recently that "even with optimal conditions for denitrification and the highest rhizobial populations found in agricultural soils, the contribution of *Rhizobium* to the total denitrification was virtually negligible as compared to other soil microorganisms". Similarly, Breitenbeck and Bremner (1989) observed that free-living cells of soybean rhizobia (*Bradyrhizobium japonicum)* can denitrify nitrate under anaerobic conditions but concluded that the population of these bacteria is likely too small to influence the rate of denitrification in soils. This brief literature review suggests that the significance of N_2O emission from legumes during N fixation remains uncertain and unproven.

When the IPCC N_2O emissions factors were first established, there were few field data quantifying N_2O emissions from biological N fixation. Duxbury et al. (1982) had reported relatively high cumulative fluxes of 2.3 and 4.2 kg N ha^{-1} $year^{-1}$ for an alfalfa field while Bremner et al. (1980) had measured lower emissions in soybean (0.3–2.0 kg N ha^{-1} $year^{-1}$). Based on these data and reports of high denitrification rates by Rhizobia (O'Hara and Daniel 1985), the IPCC emission factor for BNF was estimated at 1.25% of fixed N (IPCC 1997). Since then, field studies have added new information on N_2O emissions from legumes. Bouwman et al. (2002a), in an exhaustive summary of N_2O emissions from agricultural fields, reported that emissions from legume crops were 37% greater (though not significant statistically) than emissions from upland crops. Many of the legume fields in which the emission measurements were made also received N amendments. In the absence of non-legume controls, total N_2O fluxes often also included contributions from crop residue decomposition and other soil background sources. Consequently, Bouwman et al. (2002b) acknowledged the difficulties in assessing the contribution of BNF to N_2O emissions. Velthof and Oenema (1997) and Velthof et al. (1998) estimated N_2O–N emissions from grass-clover systems to vary between 0 and 1% of biologically-fixed N_2, probably lower than from an equivalent amount of N fertilizer because the biologically-fixed N is released slowly into the soil. This is in agreement with Corre et al. (1996) who observed that N_2O emissions from a seeded alfalfa pasture were lowest among all agricultural situations investigated in the semiarid Canadian Prairies.

Our objective was to summarize recent N_2O fluxes data from agricultural legume crops to as-

sess the emission factor associated with rhizobial nitrogen fixation.

Material and methods

We compiled from the literature pertinent field measurements of N_2O emissions in legume crops. Nitrous oxide emissions were defined as the cumulative flux reported for one field treatment during individual annual periods covered by a study (24 to 365 days). The measurements were obtained from various sources:

1. Bouwman et al. (2002a), an extensive list of flux and ancillary data from field studies published prior to 2000;
2. Additional references published before 2000 but not included in Bouwman et al. (2002a).
3. Studies published after 1999.
4. Unpublished data from Canadian studies summarized by Helgason et al. (2005).

When possible, only N_2O emissions during the growing season of the legume crops were cumulated to minimize confounding effects of residue decomposition on total emissions. However, most data sets did not separate fluxes by season, so cumulative fluxes likely include emissions that occurred prior to planting and after harvest or termination of the crop, especially for annual crops. Data from individual studies were then grouped by crop type (pure legume forage stands, grass-legume mixes and annual legumes) and further divided into unfertilized and fertilized (mineral or organic) groups. 'Unfertilized' situations included annual legumes where a small amount of N ($\leq$5,kg N ha^{-1}) was applied at planting.

Results

Our data set included 79 measurements from 33 studies (Table 1). Among unfertilized situations, there were more measurements from annual crops (41) than from pure legume forage (17) or grass-legume forage mixes (5). The fertilized legume crops involved mostly grass-legume forage mixes (11) and very few annual (2) and forage (3) legumes.

Among situations that were not fertilized, mean cumulative annual N_2O emissions were highest in pure legume forage crops (1.8 kg N ha^{-1}), intermediate in annual crops (1.0 kg N ha^{-1}) and lowest in grass-legume forages mixes (0.4 kg N ha^{-1}) (Table 1a, b, c). Emissions in legume fields fertilized with organic or mineral N sources averaged 1.5 kg N ha^{-1}. Variability between measurements was large as indicated by coefficients of variation ≥75%.

Discussion

Annual N_2O emissions associated with BNF in legume crops are typically of the order of several kg N ha^{-1} when estimated using the IPCC emission methodology (1.25% of fixed N). Using this approach, for example, Rochette et al. (2004) calculated BNF IPCC estimates ranging from 4.7 to 5.2 kg N ha^{-1} for second- or third-year alfalfa and between 3.2 and 5.0 kg N ha^{-1} for soybean. Measured N_2O emissions summarized in Table 1 a, b and c are considerably lower than these IPCC estimates. Moreover, differences between measured and IPCC-derived N_2O emissions attributed to BNF are likely even greater if we consider that field measurements also included N_2O from sources other than BNF, such as the turnover of soil organic matter and crop residue. Emissions originating from sources other than fertilizer N (so-called "background" emissions) were estimated in agricultural fields to be 0.405 kg N ha^{-1} Helgason et al. 2005), 0.82 kg N ha^{-1} (Gregorich et al. 2005) and 1 kg N ha^{-1} (Bouwman 1996). That these background emissions are of magnitude similar to fluxes reported in several annual legume crops suggests that emissions measured in legumes can be attributed largely to sources other than BNF itself. Consequently, the annual N_2O emissions derived directly from BNF itself are (1) likely less than the values reported in Table 1, and (2) much smaller than estimates obtained using the IPCC Tier I methodology.

Bolstering this observation from field flux measurements are some recent findings from process-level laboratory studies. For example, Thyme and Ambus (2004) observed that under white clover grown in an $^{15}N_2$-enriched atmosphere, only between 0 and 2% of the total N_2O emissions originated from recently-fixed N_2. Zhong et al.

Table 1. Summary of N_2O emissions from agricultural legume crops (adapted from Bouwman et al. 2002a).

Reference	Location	Crop	[e]Fertilizer type	N-rate (kg N ha^{-1})	N_2O emission (kg N ha^{-1})	Length of exp. (d)	[b]Method	[c]Freq.
A- Pure legume forage stands								
Duxbury et al. (1982)	New York, USA	Alfalfa		0	2.3	365	c	d
Duxbury et al. (1982)	New York, USA	Alfalfa		0	4.2	365	c	d
MacKenzie et al. (1998)	Montréal, Canada	Alfalfa			2		c	
MacKenzie et al. (1998)	Montréal, Canada	Alfalfa			2.83		c	
MacKenzie et al. (1998)	Montréal, Canada	Alfalfa			4.57		c	
Robertson et al. (2000)	East Lansing, USA	Alfalfa		0	3.5	265	c	
Rochette et al. (2004)	Québec city Canada	Alfalfa		0	1.45	153	c	w
Rochette et al. (2004)	Québec city Canada	Alfalfa		0	1.35	113	c	w
Rochette et al. (2004)	Québec city Canada	Alfalfa		0	0.91	191	c	w
Rochette et al. (2004)	Québec city Canada	Alfalfa		0	0.67	113	c	w
Rochette et al. (2004)	Québec city Canada	Alfalfa		0	1.12	191	c	w
Wagner-Riddle et al. (1997)	Guelph. Canada	Alfalfa		0	1.1	90	m	
Wagner-Riddle et al. (1997)	Guelph. Canada	Alfalfa		0	0.8	365	m	
Kaiser et al. (1998)	Braunschweig, Germany	Clover		0	0.96	960	c	d
Simek et al. (2004)	Ceske Budejovice. Czech Republic	Clover		0	0.9	224	c	2–3w
Van der Weerden et al. (1999)	Canterbury, New Zealand	Clover		0	0.5	100	c	
Ellert[a]	Lethbridge. Canada	Alfalfa		0	1.122	365	c	
mean					1.8			
S.D.					1.3			
B- Grass-legume forage stands								
Simek et al. (2004)	Ceske Budejovice, Czech Republic	Grass-clover		0	0.9	224	c	2–3w
Kammann et al. (1998)	Giessen, Germany	Grass-legume		0	0.2	365	c	d-w
Van der Weerden et al. (1999)	Canterbury, New Zealand	Grass-legumes		0	0.1	100	c	
Wang et al. (1997)	Wagga Wagga, Australia	Ryegass-clover		0	0.2	245	c	
Wang et al. (1997)	Wagga Wagga, Australia	Ryegass-clover		0	0.4	245	c	
mean					0.4			
S.D.					0.3			
C- Annual legume crops								
Ellert[a]	Lethbridge, Canada	Fababean		0	0.412	365	c	
Lemke et al. (2003)[a]	Swift Current, Canada	Lentil		5	0.04	226	c	w
Lemke et al. (2003)[a]	Swift Current, Canada	Lentil		5	0.11	250	c	w
Lemke et al. (2003)[a]	Three Hills, Canada	Peas		5	0.38	239	c	w
Lemke et al. (2003)[a]	Three Hills, Canada	Peas		5	0.74	239	c	w
Lemke et al. (2003)[a]	Three Hills, Canada	Peas		5	0.45	225	c	w
Lemke et al. (2003)[a]	Three Hills, Canada	Peas		5	0.38	225	c	w
Lemke et al. (2003)[a]	Three Hills, Canada	Peas		5	0.45	238	c	w
Lemke et al. (2003)[a]	Three Hills, Canada	Peas		5	0.41	238	c	w
Lemke et al. (2003)[a]	Swift Current, Canada	Chickpea		5	0.06	226	c	w
Lemke et al. (2003)[a]	Swift Current, Canada	Chickpea		5	0.16	226	c	w
Lemke et al. (2003)[a]	Swift Current, Canada	Chickpea		5	0.04	250	c	w
Lemke et al. (2003)[a]	Swift Current, Canada	Chickpea		5	0.03	250	c	w
Bremner et al. (1980)	Iowa, USA	Soybeans		0	0.34	365	c	3d/21d
Bremner et al. (1980)	Iowa, USA	Soybeans		0	0.65	365	c	3d/21d
Bremner et al. (1980)	Iowa, USA	Soybeans		0	1.35	365	c	3d/21d
Bremner et al. (1980)	Iowa, USA	Soybeans		0	1.05	365	c	3d/21d

Table 1. Continued.

Reference	Location	Crop	[e]Fertilizer type	N-rate (kg N ha^{-1})	N_2O emission (kg N ha^{-1})	Length of exp. (d)	[b]Method	[c]Freq.
A- Pure legume forage stands								
Bremner et al. (1980)	Iowa, USA	Soybeans		0	1.97	365	c	3d/21d
Bremner et al. (1980)	Iowa, USA	Soybeans		0	1.87	365	c	3d/21d
Chen et al. (2002)	Sheyang, China	Soybeans		0	0.6	124	c	w
Chen et al.(2002)	Sheyang, China	Soybeans		0	0.9	124	c	w
Gregorich [a]	Ottawa, Canada	Soybeans			1.15		c	
Gregorich [a]	Ottawa, Canada	Soybeans			1.51		c	
Gregorich [a]	Ottawa, Canada	Soybeans			0.29		c	
Gregorich [a]	Ottawa, Canada	Soybeans			0.42		c	
Jacinthe and Dick (1997)	Piketon, USA	Soybeans		0	1.18	120	c	2w
Jacinthe and Dick (1997)	Piketon, Ohio, USA	Soybeans		0	0.64	120	c	2w
Jacinthe and Dick (1997)	Piketon, USA	Soybeans		0	2.31	120	c	2w
Jacinthe and Dick (1997)	Piketon, USA	Soybeans		0	1.65	120	c	2w
MacKenzie et al. (1998)	Montréal, Canada	Soybeans			2.19		c	
MacKenzie et al. (1998)	Montréal, Canada	Soybeans			3.86		c	
MacKenzie et al. (1998)	Montréal, Canada	Soybeans			3.71		c	
Marinho et al. (2004)	Lousiana ,USA	Soybeans			1.16		c	
Rochette et al. (2004)	Québec city Canada	Soybeans		0	0.46	153	c	w
Rochette et al. (2004)	Québec city Canada	Soybeans		0	0.7	88	c	w
Rochette et al. (2004)	Québec city Canada	Soybeans		0	1	115	c	w
Rochette et al. (2004)	Québec city Canada	Soybeans		0	0.5	88	c	w
Rochette et al. (2004)	Québec city Canada	Soybeans		0	0.55	115	c	w
Rochette[a]	Montréal, Canada	Soybeans			0.9		c	
Rochette[a]	Montréal, Canada	Soybeans			1.44		c	
Wagner-Riddle et al. (1997)	Guelph, Canada	Soybeans		0	1.6	365	m	d
Mean					1.0			
S.D.					0.9			
D- Situations with N inputs other than BNF								
Ellert[a]	Lethbridge. Canada	Alfalfa		133	1.186	365	c	
Conrad et al. (1983)	Mainz, Germany	Clover	SACl	100	0.07		c	d
Conrad et al. (1983)	Mainz, Germany	Clover	SN	100	0		c	d
Misselbrook et al. (1998)	SW England	Grass-clover	Pig slurry	223	0.684	60	c	1–7d
Misselbrook et al. (1998)	SW England	Grass-clover	Pig slurry	278	0.945	60	c	1–7d
Kaiser et al. (1998)	Braunschweig, Germany	Grass-clover	CAN + UAN	175	1.06	960	c	d
Williams et al. (1999)	Grange-over-Sands, UK	Grass-clover	U + AN	250	3.2	365	c	3–4d
Kammann et al. (1998)	Giessen, Germany	Grass-legume	CAN	40	0.4	365	c	d-w
Kammann et al. (1998)	Giessen, Germany	Grass-legume	CAN	40	0.8	365	c	d-w
Kammann et al. (1998)	Giessen, Germany	Grass-legume	CAN	80	1.2	365	c	d-w
Kammann et al. (1998)	Giessen, Germany	Grass-legume	CAN	80	0.8	365	c	d-w
Kammann et al. (1998)	Giessen, Germany	Grass-legume	CAN	120	1.4	365	c	d-w
Kammann et al. (1998)	Giessen, Germany	Grass-legume	CAN	240	2.8	365	c	d-w
Kammann et al. (1998)	Giessen, Germany	Grass-legume	CAN	400	4.3	365	c	d-w
Chen et al. (2000)	Sheyang, China	Soybeans	U	35	1.99	275	c	?
Whalen et al. (2000)	Sampson County, USA	Soybeans	Pig slurry	297	3.95	24	c	2–3 p.d.
Mean					1.5			
S.D.					1.3			

[a]cited by Helgason et al. (2005)H Fertilizer type: AN, ammonium nitrate; ACl, ammonium chloride; CAN, calcium ammonium nitrate; SN, sodium nitrate; U, urea; UAN, urea-ammonium nitrate. [b]c, closed chamber method; m, micrometeorological method. [c]Frequency, frequency of sampling; d, once per day; w, once per week; m, once per month; x d, once per x days; x p.d or x p.w, x times per day/week; x h, every x hours; cont, continuous; d/w or other combinations indicate higher frequency at high [d]flux from fertilized plot minus average flux from unfertilized situations, presented as a fraction of N-application. [e]flux from fertilized plot presented as a fraction of N-application.

(2004), in a preliminary report, found that two rhizobial strains (99A1 and RGP2) were unable to denitrify in pure cultures or in pea root nodules. Emissions of N_2O from inoculated lentil and pea were not greater than from non-inoculated plants or non-legume controls. Yang and Cai (2005) reported similar N_2O emissions from pots with or without growing soybean plants until the grain-filling stage. They concluded that the process of symbiotic N fixation *per se* does not stimulate N_2O production. Further research is still merited, but we suggest that evidence to date for direct release of N_2O from BNF itself is inadequate to justify the universal adoption of this factor in global inventories of N_2O emission.

Our observation does not imply that legume crops are not an important source of N_2O; indeed, highest N_2O emissions in Table 1 were from pure legume forage crops such as alfalfa. Several studies report increased N_2O emissions in legume forage crops. Legumes in humid tropical pastures increased average N_2O emissions by 0.022 mg N m^{-2} h^{-1} compared to non-legume stands (Veldkamp et al. 1998); similar results were reported for legumes grown in a pot experiment with and without urea (Ghosh et al. 2002).

But we may not need to invoke N_2O release during BNF to explain increased N_2O emissions under legumes. Thyme and Ambus (2004), who partitioned N_2O emissions from clover in a pot study by source, reported that "mineralization of dead clover tissues is most likely a more important source of N_2O than recently-fixed N". Yang and Cai (2005) attributed increased emissions during the grain-filling stage of soybean plants to decomposition of the roots and nodules in the late growth stage. Similarly, Kilian and Werner (1996) observed that denitrification rates under N-fixing crops were correlated with soil nitrate levels; higher nitrate levels under N-fixing crops, presumably, arise from N deposition by N-fixing crops or from reduced scavenging of nitrate by the N-fixing crops. Denitrification might also be stimulated under legumes by greater release of available C (Wheatley et al. 1990; Bertelsen and Jensen 1992). Based on these findings, we propose that the increased N_2O release associated with legume crops can be attributed largely to enhanced N release from decomposing leguminous residues, including roots and nodules.

Legumes can release substantial amounts of nitrogen to the soil (Ta et al. 1986; Khan et al. 2002a, b; Janzen et al. 2003). In productive systems, nitrogen allocated to roots may amount to as much as 200 kg N ha^{-1} or more (Walley et al. 1996; Kelner et al. 1997; Rasse et al. 1999; Vinther and Jensen 2000). Additional N is added via above-ground residues and by rhizodeposition (McNeill et al. 1997). For example, Mayer et al. (2003), from a pot study, reported that rhizodeposited N accounted for 13–16% of total plant N. Upon decomposition, these organic N sources can increase nitrate and ammonium concentrations in the soil (Hossain et al. 1996a, b; Gil and Fick 2001; Mayer et al. 2004; Rochette et al. 2004), if mineralization rates exceed plant N uptake, leading to high denitrification (Pu et al. 1999, 2001) and N_2O production. By accounting fully for these nitrogen flows (and perhaps modifying current algorithms to reflect them), we may be able to reliably estimate the elevated N_2O emissions from legume crops, without resorting to poorly-understood processes of N_2O release during N_2 fixation itself.

Conclusion

In summary, there is little doubt that legumes can increase N_2O emissions, during growth (Kilian and Werner 1996) and especially after harvest (Bremner et al. 1980; Larsson et al. 1998; Rochette et al. 2004) or plowdown (Wagner-Riddle et al. 1997; Baggs et al. 2000; Millar et al. 2004). But field measurements indicate that much of this increase in emissions may be attributable to the N release from root exudates during the growing season and from decomposition of crop residues after harvest, rather than from BNF *per se*. This implies that N_2O emissions associated with the biological N fixation by legumes are smaller than previously estimated, and that, under field conditions, *Rhizobia* denitrification does not reduce significant amounts of nitrate or that N_2O represents only a minor fraction of gaseous N products.

Field flux measurements and process-level laboratory studies offer little support for the use of an emission factor for BNF by legume crops equal to that for fertiliser N. Moreover, given the uncertainty regarding the direct role of *Rhizobia* in N_2O emission under field conditions, the inclusion of this mechanism into the IPCC methodology is hard to justify. Consequently, we propose that:

1. the biological fixation process itself be removed from the IPCC N_2O inventory methodology;
2. N_2O emissions induced by the growth of legume crops be estimated solely as a function of crop residue decomposition using an estimate of above- and below-ground residue inputs, modified as necessary to reflect recent findings on N allocation.

In our view, these changes would simplify calculation of N_2O inventories, while acknowledging and capturing the important role of legumes as a potential source of N_2O.

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